Vol. 38, No. 4 (2016) 454-462

Tribology in Industry

www.tribology.fink.rs

RESEARCH

Multi-objective Optimization of Process Performances when Cutting Carbon Steel with Abrasive Water Jet

M. Radovanović [a]

[a] *University of Niš, Faculty of Mechanical Engineering, Aleksandra Medvedeva 14, 18000 Niš, Serbia.*

Keywords:

Abrasive water jet cutting
Multi-objective optimization
Perpendicularity deviation surface
Roughness
Productivity

Corresponding author:

Miroslav Radovanović
University of Niš,
Faculty of Mechanical Engineering,
Aleksandra Medvedeva 14,
18000 Niš, Serbia.
E-mail: mirado@masfak.ni.ac.rs

A B S T R A C T

Multi-objective optimization of process performances (perpendicularity deviation, surface roughness and productivity) when cutting carbon steel EN S235 with abrasive water jet is presented in this paper. Cutting factors (abrasive flow rate, traverse rate and standoff distance) were determined when perpendicularity deviation and surface roughness are minimal and productivity is maximal. Multi-objective genetic algorithm (MOGA) was used for the determination set of nondominated optimal points, known as Pareto front.

1. INTRODUCTION

There are some machining technologies for contour cutting metal or non metal sheets. Flame cutting, plasma cutting, laser cutting, wire EDM and water jet cutting are more applicable machining technologies for contour cutting sheets. Abrasive water jet (AWJ) cutting is a modern nonconventional machining technology that enables contour cutting a wide range of materials and thickness. AWJ cutting has advantages over the other contour cutting technologies such as: no thermal distortion, no heat affected zone, small cutting force, minimum stress on the workpiece, high flexibility, high versatility and has been proven to be an effective technology for machining various engineering materials and wide range of thickness. Thickness which can be cut are 100 mm for stainless steel and 120 mm for aluminum, for water pressure of 400 MPa. With AWJ it is possible to cut random contours in thick, middle and thin sheets, such as very fine tabs and filigree structures. Tolerances of ±0.1 mm can be realized in metal cutting. [1]

Process of AWJ cutting is based on material removal from the workpiece by erosion. High speed water jet stream accelerates abrasive particles and those particles erode the material.

In AWJ cutting high pressure pump via accumulator and high pressure tubing directs the pressurized water to the cutting head. Types of pumps and levels of pressure are classified by water jet industry as:

- Low pressure, p<10000 psi (p<690 bar, p<69 MPa)
- Medium pressure, 10000<p<15000 psi (690<p<1030 bar, 69<p<103 MPa)
- High pressure, 15000<p<40000 psi (1030<p<2760 bar, 103<p<276 MPa)
- Ultra high pressure, 40000<p<75000 psi (2760<p<5170 bar, 276<p<517 MPa)
- Hyper pressure, p>75000 psi (p>5170 bar, p>517 MPa).

There are two types of high pressure pumps: direct drive pumps and intensifier pumps. Direct drive pumps generally are found in industrial applications with pressure to 380 MPa. These pumps use an electric motor to turn a crankshaft that moves three or more pistons that create the water pressure. But, the most common pumps in industrial applications are intensifier pumps. Intensifier pumps are called intensifiers because they use the concept of pressure intensification to generate the desired water pressure. These pumps use hydraulics to apply a certain amount of oil pressure on one side of a piston of a certain diameter. On the water side of the pump, the diameter of the piston is much smaller. The difference in the surface area between the hydraulic side and the water side gives a multiplication factor, or intensification, to the pressure from the oil side. Most intensifier pumps have an intensification ratio of 20 times. Intensifier pumps generally are found in pressure applications to 600 MPa. With intensifier pump can be achieved hyper pressure. Water jet pumps are specified in either horsepower (HP) or kilowatts (kW) to indicate the size of the electric motor that creates the force to pressurize the water. High pressure pumps power range is from 15 HP (11 kW) to 200 HP (150 kW). Most common AWJ machine tools are with power between 30 HP (22 kW) and 100 HP (75 kW). Cutting head consists of orifice, mixing chamber and focusing tube. Orifice is with diameter of 0.15 to 0.35 mm and is made of sapphire, ruby or diamond. Focusing tube is with diameter of 0.54 to 1.1 mm, length of 50 to 100 mm, and is made of tungsten carbide. Water is pressed out of the orifice in form of very thin jet at a high speed. Speed of water jet can calculate using equation:

$$v_{wj} = \alpha \sqrt{\frac{2p}{\rho_w}} \,. \qquad (1)$$

where are: v_{wj}-speed of water jet in m/s, α-correction factor (0.9-0.98), p-water pressure in Pa, ρ_w-density of water in kg/m^3.

Abrasive particles are added to water jet in mixing chamber of the cutting head. There are two methods to add abrasive particles to water jet: suspension and injection. The suspension method (direct, indirect or bypass) is used in industry only at pressures of up to 70 MPa. Today the injection method is mainly used for industrial applications with operating pressures of up to 400 MPa. The high velocity of the water jet creates a Venturi effect or vacuum in the mixing chamber located immediately beneath the orifice. Abrasive particles are metered from a mini-hopper through a plastic tube down to the cutting head and are sucked into the water jet stream in the mixing chamber. Abrasive particles are accelerated with high speed water jet. Abrasive particles are mixed with the water jet creating abrasive water jet. Speed of abrasive water jet can calculate using equation [2,4]:

$$v_{awj} = \eta \frac{v_{wj}}{1 + \frac{m_a}{m_w}} \,. \qquad (2)$$

Where are: v_{awj}-speed of abrasive water jet in m/s, η-momentum loss factor (0.65-0.85), v_{wj} - speed of water jet in m/s, m_a-abrasive mass flow rate in kg/s, m_w-water mass flow rate in kg/s.

Abrasive water jet is focused by a focusing tube. Focusing tube directs the abrasive water jet to cut the workpiece. Abrasive water jet cuts workpiece along the programmed contour using CNC (computer numerical control) motion system of the machine. Scheme of the AWJ cutting is shown in Fig. 1. [2,3].

For evaluation of the AWJ cutting, the greatest influence has a group of geometric characteristics of the workpiece issued in cutting process. The geometric characteristics are: form accuracy, dimensional accuracy and cut quality. Cut quality relates to form of kerf and cut surface. Terms in AWJ cutting, according ISO/TC 44 N 1770 [5], are shown in Fig. 2, where are: R_a-surface roughness, f-pitch of drag line, g-burr, h_f-fine cut, h_r-remaining surface, n-drag line, r_k-edge radius, s-jet direction, sb-jet affected zone, t-workpiece thickness, u-perpendicularity or angularity tolerance. Cut quality limits AWJ cutting application. The perpendicularity deviation and surface roughness of the cut are the most significant characteristics of the cut quality.

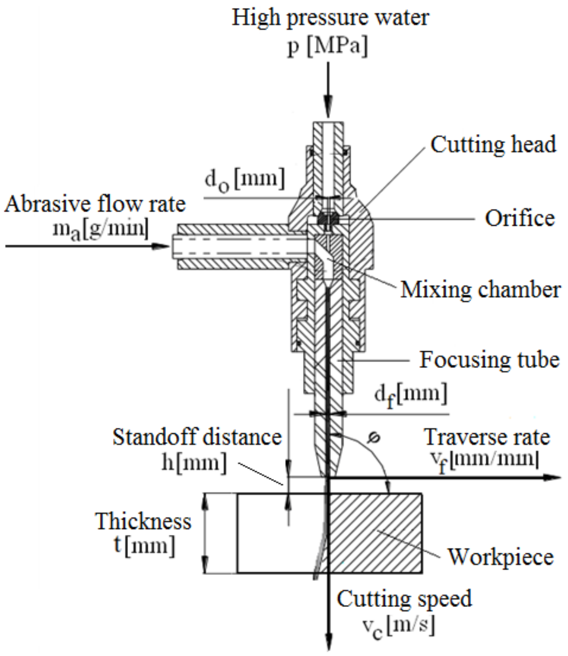

Fig. 1. Scheme of AWJ cutting.

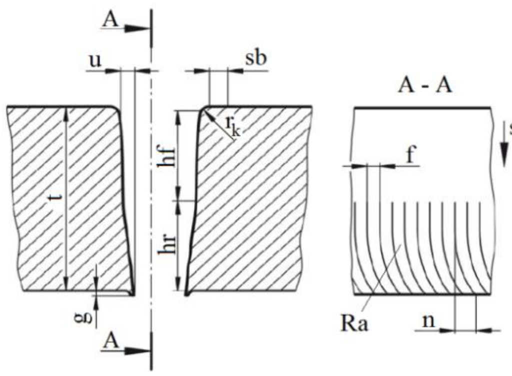

Fig. 2. Terms related to kerf and cut surface.

There are some studies of multi-objective optimization of abrasive water jet machining and multi-objective optimization using genetic algorithms (GA). Aultrin J. and Anand D. in [6] studied abrasive water jet cutting of aluminum alloy 6061. They have investigated the effect of factors (water pressure, abrasive flow rate, orifice diameter, focusing tube diameter and standoff distance) on performances (material removal rate and surface roughness). using Response Surface Methodology (RSM). Two objectives (material removal rate and surface roughness) are optimized by using Grey Relation Analysis (GRA).

Chakravarthy P. and Babu N. in [7] studied abrasive water jet cutting of granite. They have investigated the effect of factors (water pressure, traverse rate and abrasive flow rate) on performance (depth of cut). In order to determine the Pareto front for the multi-objective optimization problem with three objectives (cost of production, rate of production and consumption of abrasives) they have applied a new approach based on the principles of fuzzy logic and genetic algorithm (GA).

Chaitanya M. and Krishna A. in [8] studied laser cutting of aluminum alloy 7075. They have investigated the effect of factors (pulse-power, pulse frequency, pulse width and assist gas pressure) on performances (surface roughness and heat affected zone). In order to determine the Pareto front for the multi-objective optimization problem with two objectives (surface roughness and heat affected zone) they have applied GA based non dominated sorting algorithm-II (NSGA-II).

Soni V. et al. in [9] studied turning of aluminum using carbide cutting tool. They have investigated the effect of factors (depth of cut, feed and cutting speed) on performances (material removal rate and surface roughness). In order to determine the Pareto front for the multi-objective optimization problem with two objectives (material removal rate and surface roughness) they have applied multi-objective genetic algorithm (MOGA).

Bouzakis K. et al. in [10] studied milling of aluminum alloy 2024 using cemented carbide face milling cutting tool. They have investigated the effect of factors (depth of cut, feed rate and cutting speed) on performances (machining cost and machining time). In order to determine the Pareto front for the multi-objective optimization problem, for rough milling with three objectives (production cost, production time and distance from maximum power) and for finish milling with three objectives (production cost, production time and cutting tool deflection), they have applied multi-objective genetic algorithm (MOGA).

2. AWJ CUTTING FACTORS AND PERFORMANCES

AWJ cutting is a complex process with many factors that determine performances. Mechanism of erosion depends on the level of various process factors and is explained by multiple phenomena. AWJ cutting factors can be classified into six categories, Fig. 3:

- Factors of workpiece (material type, thickness, chemical structure, hardness, toughness, grain size, tolerances, roughness).
- Factors of water system (pump pressure, water flow rate, water purity, accumulator volume, high pressure tubing).
- Factors of abrasive system (abrasive material type, abrasive hardness, abrasive particle size, abrasive particle shape, abrasive particle size distribution, abrasives input method).
- Factors of cutting head (orifice diameter, orifice material, focusing tube diameter, focusing tube length, focusing tube material).
- Factors of motion system (precision, accuracy, stiffness, working conditions).
- Factors of process (water pressure, traverse rate, abrasive flow rate, standoff distance, impact angle).

AWJ cutting performances can be classified into five categories, Fig. 4:

- Process performances (orifice wear, focusing tube wear, temperature, noise, vibration).
- Quality performances (form deviations, dimension deviations, cut quality: kerf depth, kerf width, perpendicularity deviation of the cut surfaces-kerf taper, striations, burr, edge radius, jet affected zone, surface roughness).
- Productivity performances (machining time, productivity).
- Economy performances (manufacturing cost, power consumption, abrasives consumption, water consumption).
- Ecology performances (noise, pollution, recycling).

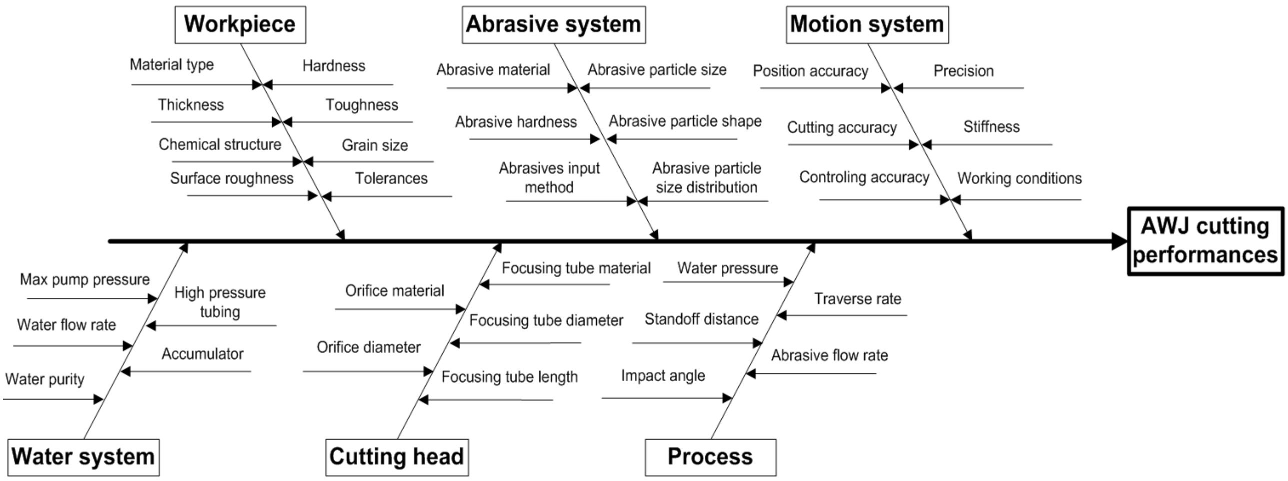

Fig. 3. AWJ cutting factors.

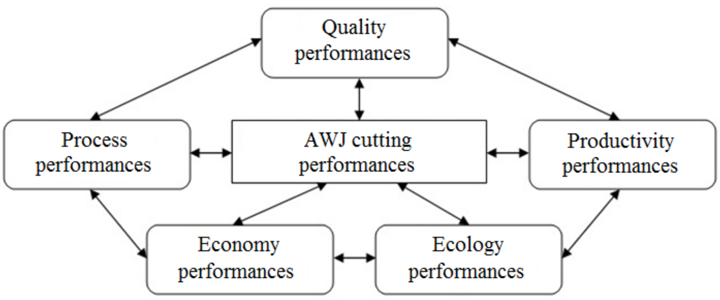

Fig. 4. AWJ cutting performances.

Some of the most important performances in AWJ cutting are perpendicularity deviation, surface roughness and productivity.

Perpendicularity deviation of the cut surfaces (kerf taper) is distance between two parallel straight lines (tangents) between which the cut surface profile is inscribed, and within the set angle (e.g. 90° in the case of vertical cuts). Perpendicularity deviation includes and the flatness deviations.

Surface roughness is a measure of the technological quality of the cut. Commonly arithmetic average roughness (R_a) was used to describe surface roughness. R_a is defined as the arithmetic value of the profile from centerline along the sampling length.
Productivity is defined as:

$$Q = t v_f \,. \tag{3}$$

where are: Q (mm²/min)-productivity, t (mm)-material thickness, v_f (mm/min)-traverse rate.

Productivity in contour cutting of sheets is defined as cut surface productivity, i.e. surface of the cut in unit of time. The goal in contour cutting is to have maximum cutting length with minimum kerf width.

3. EXPERIMENTAL RESEARCH

Experimental research was planed and realized in order to define regression equations for performances (perpendicularity deviation and surface roughness) in correlation of factors (abrasive flow rate, traverse rate and standoff distance). The equipment used for experimentation was abrasive water jet cutting machine Hydro Jet Eco 0615 with high pressure pump of 150 MPa, power of 7.5 kW and water flow rate of 2.4 l/min. Cutting head was composed of orifice made of sapphire with inner diameter of 0.35 mm and focusing tube made of tungsten carbide with inner diameter of 1.02 mm and length of 76 mm. Jet impact angle was 90°. All experiments were conducted with water pressure of 150 MPa. Abrasive material was Garnet mesh 80 (≈ 177 μm). Workpiece material was carbon steel EN S235, thickness of 6.5 mm.

Design of experiment was conducted using full factorial design 2^3 (three factors each on two levels) with center point. Control factors are: abrasive flow rate (m_a), traverse rate (v_f), and standoff distance (h). Control factors and their levels are shown in Table 1. [12]

Table 1. Control factors and levels

Code	Control factors	Levels		
		-1	0	+1
A	Abrasive flow rate, m_a (g/min)	300	500	700
B	Traverse rate, v_f (mm/min)	50	100	150
C	Standoff distance, h (mm)	1	3	5

Three control factors are arranged in design of experiment with 9 runs (8 runs are for base design and 1 run for center point). Measured performances are: perpendicularity deviation (u) and surface roughness (R_a). Perpendicularity deviation has measured using optical microscope Metkon and surface roughness has measured using surface measuring instrument Hommel Tester T500. Design of experiment with factor levels and measured values of performances, is presented in Table 2.

Table 2. Design of experiment and results.

Run	Control factors			u (mm)	R_a (μm)
	A	B	C		
1	-1	-1	-1	0.07	4.12
2	-1	-1	1	0.11	4.50
3	-1	1	-1	0.17	5.18
4	-1	1	1	0.14	5.13
5	1	-1	-1	0.20	4.23
6	1	-1	1	0.21	4,45
7	1	1	-1	0.30	4.99
...	...	...	...	...	...
9	0	0	0	0.26	4.22

Analysis of variance (ANOVA) was carried out to find the relative effect of factors and interactions on performances perpendicularity deviation and surface roughness. If $p<0.05$ the factors have a significant effect on performance. If $p>0.10$ the factors have not an effect on performance. If $0.05<p<0.10$ the factors have a moderate effect on performance. Analysis of variance for perpendicularity deviation (u) is shown in Table 3. Standard F table value at 95 % confidence level is $F_{0.05,1,3}=10.13$.

From Table 3 can see that factors: abrasive flow rate, traverse rate and standoff distance have a strong (clearly statistically significant) effect on the perpendicularity deviation with contribution of 90.28 %. Traverse rate is the most significant factor affecting the perpendicularity deviation with contribution of 51.04 %. Abrasive flow rate affects with contribution of 34.70 % and standoff distance affects with contribution of 4.54 % on the perpendicularity deviation. Some interactions have significant effect on the perpendicularity deviation. Interaction abrasive flow rate-traverse rate affects with contribution of 1.27 %, abrasive flow rate-standoff distance affects with contribution of 5.67 % and interaction abrasive flow rate-traverse rate-standoff distance affects with contribution of 1.90 % on the perpendicularity deviation.

Table 3. Analysis of variance for u.

Source	DF	SS	MS	F	p	%
Main effects	3	0.07184	0.02394	261.23	0.000	90.28
A	1	0.02761	0.02761	301.23	0.000	34.70
B	1	0.04061	0.04061	443.05	0.000	51.04
C	1	0.00361	0.00361	39.41	0.008	4.54
2-Way Interactions	3	0.00584	0.00194	21.23	0.016	7.34
AB	1	0.00101	0.00101	11.05	0.045	1.27
AC	1	0.00451	0.00451	49.23	0.006	5.67
BC	1	0.00031	0.00031	3.41	0.162	0.39
3-Way Interaction	1	0.00151	0.00151	16.50	0.027	1.90
ABC	1	0.00151	0.00151	16.50	0.027	1.90
Curvature	1	0.00010	0.00010	1.14	0.365	0.13
Error	3	0.00027	0.00009	-	-	0.34
Total	11	0.07957	-	-	-	100

DF-degree of freedom, SS-sum of square, MS-mean square F-variance ratio, p–value, %-percent contribution

Regression equation for perpendicularity deviation, with coefficient of determination of R^2=99.65%, is:

$$u = -0.106562 + 0.000434375 m_a + 0.00283125 v_f + 0.0090625 h - 0.0000031875 m_a v_f - 0.000009375 m_a h + 0.0000006875 m_a v_f h \quad (4)$$

Analysis of variance for surface roughness (R_a) is shown in Table 4. Standard F table value at 95 % confidence level is $F_{0.05,1,3}$=10.13.

From Table 4 can see that factors: abrasive flow rate and traverse rate have a strong (clearly statistically significant) effect on the surface roughness with contribution of 65.35 %.

Table 4. Analysis of variance for R_a.

Source	DF	SS	MS	F	p	%
Main effects	3	1.33330	0.44443	4848	0.000	65.39
A	1	0.06845	0.06845	746	0.000	3.36
B	1	1.26405	1.26405	13789	0.000	61.99
C	1	0.00080	0.00080	8.73	0.060	0.04
2-Way Interactions	3	0.03225	0.01075	117	0.001	1.58
AB	1	0.02645	0.02645	288	0.000	1.30
AC	1	0.00080	0.00080	8.73	0.060	0.04
BC	1	0.00500	0.00500	54.55	0.005	0.24
3-Way Interaction	1	0.02000	0.02000	218	0.001	0.98
ABC	1	0.02000	0.02000	218	0.001	0.98
Curvature	1	0.65340	0.65340	7128	0.000	32.04
Error	3	0.00028	0.00009	-	-	0.01
Total	11	2.03922	-	-	-	100

Traverse rate is the most significant factor affecting the surface roughness with contribution of 61.99 %. Abrasive flow rate affects with contribution of 3.36 %. Standoff distance has moderate effect with contribution of 0.04 %. Some interactions have significant effect on the surface roughness. Interaction abrasive flow rate-traverse rate affects with contribution of 1.30 %, traverse rate-standoff distance affects with contribution of 0.24 %, abrasive flow rate-traverse rate-standoff distance affects with contribution of 0.98 % on the surface roughness. Interaction abrasive flow rate-standoff distance has moderate effect with contribution of 0.04 % on the surface roughness. Regression equation for surface roughness, with coefficient of determination of R^2=99.99 %, is:

$$R_a = 3.01125 + 0.0017125 m_a + 0.015325 v + 0.1325 h - 0.00001325 m_a v - 0.000225 m_a h - 0.0015 v h + 0.0000025 m_a v h \quad (5)$$

4. MULTI-OBJECTIVE OPTIMIZATION

Procedure of multi-objective optimization has four phases. First phase is mathematical modelling of performances in correlation of the factors. Second phase is determining optimization problem. In second phase objectives are selected and constraints are defined. Third phase is selection of method for solution of optimization problem. Fourth phase is solution of optimization problem.

Mathematical model of the multi-objective optimization was defined with goal to minimize perpendicularity deviation and surface rougness and maximize productivity. Mathematical model of the multi-objective optimization is:

- Objective functions:

$$f_1 - \min(u)$$
$$f_2 - \min(R_a)$$
$$f_3 - \max(Q)$$

- Constraints:

$$m_{a,min} \le m_a \le m_{a,max}$$
$$v_{f,min} \le v_f \le v_{f,max}$$
$$h_{min} \le h \le h_{max}$$

Mathematical model of the multi-objective optimization for this study has form:

- Objective functions:

$$f_1 - \min\begin{pmatrix} u = -0.106562 + 0.000434375 m_a \\ + 0.00283125 v_f + 0.0090625 h \\ - 0.0000031875 m_a v_f - 0.000009375 m_a h \\ + 0.0000006875 m_a v_f h \end{pmatrix}$$

$$f_2 - \min\begin{pmatrix} R_a = 3.01125 + 0.0017125 m_a + 0.015325 v_f \\ + 0.1325 h - 0.00001325 m_a v_f \\ - 0.000225 m_a h - 0.0015 v_f h \\ + 0.0000025 m_a v_f h \end{pmatrix}$$

$$f_3 - \min(-Q = -6.5 v_f)$$

- Constraints

$$300 \le m_a \le 700$$
$$50 \le v_f \le 150$$
$$1 \le h \le 5$$

Table 5. Parameters of the multi-objective genetic algorithm.

Population type	Double vector
Population size	50
Creation function	Constraint dependent
Selection	Selection function: Tournament, Tournament size: 2
Reproduction	Crossover fraction: 0.8
Mutation	Mutation function: Constraint dependent
Crosover	Crossover function: Intermediate, Ratio: 1.0
Migration	Direction: Forward, Fraction: 0.2, Interval: 20
Multiobjective problem settings	Pareto front population fraction: 0.35
Stopping criteria	Generations: 100*number of variables
Current iteration	116

Nondominated points, generated by multi-objective genetic algorithm solver, have plotted in form of the Pareto front, Fig. 5.

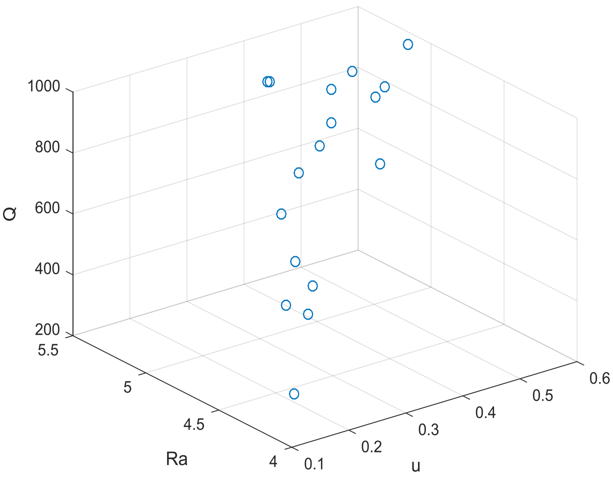

Fig. 5. Pareto front points.

Listing of the Pareto front points obtained as outcomes from the optimization process presented in Table 6.

Table 6. Pareto front points.

Index	f1 u (mm)	f2 R_a (μm)	f3 Q (mm²/min)	x1 m_a (g/min)	x2 v_f (mm/min)	x3 h (mm)
1	0.134	4.120	325.000	300.000	50.000	1.000
2	0.356	5.153	974.877	507.442	149.981	1.069
3	0.251	4.563	588.735	339.636	90.113	1.965
4	0.590	5.121	972.039	579.961	149.545	4.711
5	0.526	5.030	891.874	573.326	137.211	4.248
6	0.353	5.153	974.757	507.461	149.963	1.016
7	0.469	4.841	716.290	600.770	110.198	4.359
8	0.507	5.014	873.178	585.376	134.335	3.984
9	0.434	5.033	937.266	367.289	144.195	3.377
10	0.201	4.431	505.085	325.091	77.705	1.163
11	0.267	4.723	696.890	309.600	107.214	1.426
12	0.487	5.101	947.547	580.924	145.776	3.217
13	0.232	4.408	465.341	364.071	71.591	2.582
14	0.382	4.913	806.165	482.089	124.025	2.598
15	0.421	4.980	844.410	561.978	129.909	2.756
16	0.259	4.474	524.641	332.475	80.714	3.201
17	0.333	4.865	757.053	501.921	116.470	1.747

From Table 6 it is evident that near optimal factor levels for rough cutting carbon steel EN S235 with abrasive water jet can be selected as: abrasive flow rate of m_a=507.442 g/min, traverse rate of v_f=149.981 mm/min and standoff distance of h=1.069 mm. For these factor levels, perpendicularity deviation is u=0.356 mm, surface roughness is R_a=5.153 μm and productivity is Q=974.877 mm^2/ min.

From Table 6 it is evident that perpendicularity deviation u is important performance for finish cutting carbon steel EN S235 with abrasive water jet. Surface roughness is R_a≤6.3 μm. For example, if tolerance of dimensions is T=±0.25 mm (u≤0.25 mm) and R_a≤6.3 μm, than the near optimal factor levels can select as: abrasive flow rate of m_a=325.091 g/min, traverse rate of v_f=77.705 mm/min and standoff distance of h=1.163 mm. For these factor levels, perpendicularity deviation is u=0.201 mm, surface roughness is R_a=4.431 μm and productivity is Q=505.085 mm^2/ min.

5. CONCLUSION

AWJ cutting is a modern nonconventional machining technology. Cut quality limits AWJ cutting application. Some of the most important performances in AWJ cutting are perpendicularity deviation, surface roughness and productivity. To optimize AWJ cutting performances it is essential to have knowledge of the perpendicularity deviation and surface roughness in relation to process factors. When AWJ cutting carbon steel EN S235 regression equations for perpendicularity deviation and surface roughness in relation of the abrasive flow rate, traverse rate and standoff distance have defined using experimental research. For minimize perpendicularity deviation and surface rougness and maximize productivity, mathematical model of the multi-objective optimization was defined. Multi-objective genetic algorithm solver was selected as method for solution of the optimization problem. For rough cutting the near optimal factor levels can select as: m_a=507.442 g/min, v_f=149.981 mm/min and h=1.069 mm. For these factor levels perpendicularity deviation is u=0.356 mm, surface roughness is R_a=5.153 μm and productivity is Q=974.877 mm^2/min. For finish cutting, if T=±0.25 mm and R_a≤6.3 μm, the near optimal factor levels can select as: m_a=325.091 g/min, v_f=77.705 mm/min and h=1.163 mm. For these factor levels perpendicularity deviation is u=0.201 mm, surface roughness is R_a=4.431 μm and productivity is Q=505.085 mm^2/min.

Acknowledgement

The paper is a result of the technological project TR35034 which is supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia.

REFERENCES

[1] M. Radovanović and M. Madić, 'Optimizing factor levels based on cost in abrasive water jet cutting using GA', *Methods and Techniques for Industrial Development*, University of Maribor, Faculty of Mechanical Engineering, Politecnico di Torino, Maribor, Slovenia, pp. 17-30, 2015.

[2] M. Radovanović, 'Investigation of surface roughness in abrasive water jet cutting using Shainin method', *Tribological Journal BULTRIB*, vol. 5., no. 5, pp. 105-110, 2015.

[3] M. Radovanović and E. Herghelegiu, 'Perpendicularity deviation and surface roughness in abrasive water jet cutting of carbon steel', *Nonconventioal Technologies Review*, no. 2, pp. 39-44, 2016.

[4] B. Nedić and J. Baralić, 'The wear of the focusing tube and the cut-surface quality', *Tribology in Industry*, vol. 32, no. 2, pp. 38-43, 2010.

[5] ISO/TC 44 N 1770, Water jet cutting-Geometrical product specification and quality, 2010.

[6] J. Aultrin and D. Anand, 'Multi-objective optimization of abrasive water jet machining of aluminum 6061 alloy by Grey Relational Analysis', *Journal of Chemical and Pharmaceutical Sciences*, vol. 9, no. 1, pp. 410-417, 2016.

[7] P. Chakravarthy and N. Babu, 'A new approach for selection of optimal process parameters in abrasive water jet cutting', *Materials and Manufacturing Processes*, vol. 14, no. 4, pp. 581-600, 2007.

[8] M. Chaitanya, A. Krishna, Multi-objective optimization of laser beam cutting process, *International Journal of Research in Mechanical Engineering & Technology - IJRMET*, vol. 3, no. 2, pp. 279-290, 2013.

[9] V. Soni, S. Mandal and B. Singh, 'Process parameters optimization in turning of aluminum using a new hybrid approach', *International Journal of Innovative Science, Engineering & Technology - IJISET*, vol. 1, no. 3, pp. 418-423, 2014.

[10] K. Bouzakis, R. Paraskevopoulou and G. Giannopoulos, 'Multi-objective optimization of cutting conditions in milling using genetic algorithms', in: *3rd International Conference on Manufacturing Engineering - ICMEN-2008*, 1-3 October, Chalkidiki, Greece, pp. 763-774, 2008.

[11] E. Herghelegiu, 'Contributions to the optimization of the water jet working parameters', *Dissertation*, University "Vasile Alecsandri" of Bacau, Romania, 2011.

[12] M. Madić, M. Radovanović and B. Nedić, 'Correlation between Surface Roughness Characteristics in CO_2 Laser Cutting of Mild Steel', *Tribology in Industry*, vol. 34, no. 4, pp. 232-238, 2012.

[13] M. Radovanović, 'Investigation on surface roughness of carbon steel machined by abrasive water jet using Taguchi method', *Tribological Journal BULTRIB*, vol.4, pp. 47-54, 2014.

[14] P. Janković, M. Radovanović, J. Baralić and B. Nedić, 'Prediction model of surface roughness in abrasive water jet cutting of aluminium alloy', *Journal of the Balkan Tribological Association*, vol. 19, no 4, pp. 585-595, 2013.

[15] M. Radovanović, P. Janković and M. Madić, 'Predictive models of traverse rate in abrasive water jet cutting based on RA and GA', *Academic Journal of Manufacturing Engineering*, vol. 10, no. 1, pp. 107-112, 2012.

[16] M. Radovanović, 'Abrasive Waterjet Cutting cost', *Nonconventional Technologies Review*, no. 1, pp. 97-102, 2007.